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A Comparison of Lightning Network Data With Surface Weather Observations

H. A. BROWN

9 May 1989

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GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731-5000

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UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

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This study was initiated in response to an Air Force (AF) need for meteorological sensors to automate the aviation weather observation. The objective was to demonstrate the effectiveness of a lightning detection network in providing a real-time data base from which automated observations of thunderstorms and lightning in the vicinity of an air base can be derived.

A direction-finding (DF) cloud-to-ground (CG) lightning detection network (LDN) operated by the State University of New York at Albany provided a data base of CG lighting locations in the northeastern United States for the months of July and August, 1986. Copies of the original weather observation forms from twenty-five AF weather stations in the same area and time period provided a data base of thunderstorm and lighting observations for comparison.

The lighting data base was analyzed for strike events located within 15 nm of each weather station. If the fifteen minute period lapsed without another strike, the event was ended. Events were categorized as single- or multiple-strike events and the duration of the events tabulated.

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The weather observation data base was analyzed for thunderstorm events. The beginning time, ending time and duration of the events were tabulated as well as the type of lightning that was reported with each observation. A tangential study showed that the observations of lightning-type with thunderstorms were biased toward nocturnal periods, therefore the decision was made to eliminate this categorization from the study.

Chronological comparison of the two data bases, using the weather observation data base as 'ground truth', generated 4 × 4 contingency tables of the combinations of thunderstorm-lightning events. Four parameters were derived from the statistical evaluation of the contingency tables: (1) Probability-of-Detection, (POD); (2) False-Alarm-Rate, (FAR); (3) Missed Threat Rate, (MTR); and (4) Critical Success Index, (CSI).

Two case studies were performed with the lightning strike data base. The first case combined single- and multiple-strike events as valid events for comparison. The second case utilized only the multiple-strike events as valid periods for comparison. As an additional measure of the impact of DF coverage on the effectiveness of the lightning network, the evaluation parameters were stratified by the number of DFs providing coverage to each station. In Case 1 the POD ranged for 31% in the 0-1 DF class to 98% in the 6-7 DF class (MTR ranged from 69% to 2%). The FAR ranged from 70% in the 0-1 DF class to 30 to 50% in the higher DF classes. The Critical-Success-Index (CSI) incorporates the results of the above tests and showed the lowest CSI, 17% in the 0-1 DF class and the highest CSI, 54% in the 2-3 DF class.

The second case study eliminated all false alarms generated by single-strike events that did not verify with thunderstorm observations. On the other hand it generated missed threats when a single-strike event verified with 'ground truth'. The results showed that the 0-1 DF class stations had a POD drop to 15%, while the 6-7 DF class had a POD drop of 89%. The most dramatic changes occurred in the FAR, in which improvements ranged from 24% in the 2-3 DF class to 19% in the 6-7 DF class. The Critical-Success-Index improved significantly (10 to 15%) in all of the higher DF classes.

Several cases are shown in the Appendix to illustrate the variety of comparative situations that were noted in the analysis of the data bases.

Preface

The efforts of Mr. Scott Spratt in the tabulation and processing of the data for this study are gratefully acknowledged. Appreciation is also extended to Dr. Michael Kraus and Mr. Donald Grantham for their helpful comments and suggestions.

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1. INTRODUCTION

This study was initiated by the Air Force Geophysics Laboratory (AFGL) in response to a requirement expressed in an Air Force Communications Command Required Operational Capability (AFCC ROC 801-77). This requirement was formalized in Headquarters, United States Air Force, Program Management Directive No. 1017/PE63707F, which directed the development and testing of sensors and techniques to automate the aviation weather observation. The sensors and techniques that met Air Force requirements would be incorporated in the Automated Observation System (AOS) and become a direct source of weather observations for the Automated Weather Distribution System (AWDS). In the present-day Air Force, aircraft operations, as well as base operations, have an increasing requirement for accurate and prompt updates on weather conditions in the immediate environment of an air base. The utilization of manpower to meet this need is difficult to justify when technological advances in weather sensor design have progressed to the point that instruments are capable of observing local weather conditions automatically and accurately in real time.

The surface aviation weather observation consists of numerous elements that are currently amenable to automation. These elements include sea-level pressure, temperature, dew-point, wind direction, wind speed and altimeter setting. There are four elements of the observation, however, that require further sensor research and development. The four elements are cloud observations and cloud ceiling definition; prevailing and sector visibility determination; weather and obstructions-to-vision

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discrimination; and finally, a miscellaneous category of observations that provide a more detailed account of the variabilities that exist in the first three items. This element, entitled Remarks, also includes comments on lightning type, frequency and location, and information on thunderstorms, for example, location and direction of movement. AFGL's plans call for the acquisition or development of candidate or prototype sensors for each element and an evaluation to determine their ability to meet Air Force requirements.

This study focuses on the solution to the automated detection of thunderstorms at an air base. It is based on a comparison of observations of lightning made by an automated computer-controlled lightning detection network with observations of thunderstorms and lightning made by observers at a number of Air Force bases. The primary objective of the study is to demonstrate the effectiveness of a lightning detection network in providing a real-time data base from which automated observations of thunderstorms and lightning can be derived.

2. LIGHTNING OBSERVATIONS

2.1 Lightning Systems

An operational comparative study of lightning warning systems in 1979[1] responded to a concern over a number of incidents of lightning-induced premature explosions in open-pit mining operations that used electrical detonators. Six commercial lightning-detection systems that utilized different techniques were tested. They were a sferics probe, a corona point, a radioactive probe, a field mill, an azimuth/range locator, and a triangulation location system. The tests were conducted at three sites with dissimilar thunderstorm regimes. The systems were compared using five evaluation parameters: (1) advance warning time; (2) false alarm rate; (3) failure-to-alarm rate; (4) detection probability; and (5) time to clear after a hazard had passed. The best performance was achieved by the triangulation (direction finder) location system. A concern was expressed, however, on its 6 to 9 percent failure-to-alarm-rate.

The electro-magnetic direction-finding (DF) technique, developed in the 1970's, has been widely accepted for its utility in forest fire detection[2] and electrical power operations.[3,4] Another lightning

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1. Johnson, R.L., Janota, D.E., and Hay, J.E. (1982) An operational comparison of lightning warning systems, *J. Appl. Meteorol.* **21**:703-707.
2. Krider, E.P., Noggle, R.C., Pifer, A.E., and Vance, D.L. (1980) Lightning direction-finding systems for forest fire detection, *Bull. Amer. Meteorol. Soc.* **61**:980-986.
3. Maier, M.W., Binford, R.C., Byerly, L.G., Krider, E.P., Pifer, A.E., and Uman, M.A. (1983) Locating cloud-to-ground lightning with wideband magnetic direction finders. Preprints, Fifth Symposium on Meteorological Observations and Instrumentation (Toronto), AMS, Boston, pp. 497-504.
4. Orville, R.E., Henderson, R.W., and Bosart, L.F. (1983) An east coast lightning detection network, *Bull. Amer. Meteorol. Soc.* **64**:1029-1037.

detection system has also been developed[5] that uses time-of-arrival (TOA) techniques to solve the location of a strike. Accuracies of lightning strike locations and detection efficiencies of networks have, in the past, largely been produced through theoretical studies[6] and estimates. Recently, however, a comparative study of a DF and TOA system was completed.[7] The accuracy of lightning strike locations and the detection efficiency of each system was determined by comparing their strike data with an independent data base of cloud-to-ground strike times and locations. The typical detection efficiency obtained within or near the DF network was 55 - 75 percent. Some storms had detection efficiencies as high as 80 - 90 percent, but others were as low as 20 - 40 percent. The wide variation was attributed to storms with different lightning characteristics. DF software has been written to reject strikes with cloud-to-cloud characteristics. The storms that were observed with low detection efficiencies produced cloud-to-ground lightning strikes with characteristics similar to cloud-to-cloud strikes. The typical detection efficiency obtained from the TOA system was, in general, lower (values of 40 - 55 percent) than the DF system. The accuracy of lightning strike locations was also better in the DF system (less than 10 km error) than in the TOA system (10 to 20 km error). At greater distances (250 km), however, the TOA system was more accurate.

2.2 Lightning Detection Network

A DF-type lightning location network has been operating in the northeastern United States since 1982.[4] The network, operated by the State University of New York at Albany (SUNY-Albany) under the direction of Professor Richard E. Orville, has undergone extensive expansion since its inception and now covers the eastern third of the United States. The SUNY-Albany group has developed a highly sophisticated automated network over the ensuing years. Utilization of signals from all DF's in conjunction with optimization techniques in calculating real-time strike locations are some of the attributes that distinguish the network. The direction-finding sensors used in the network have been described in many articles[2,3,4] and are manufactured by the Lightning Location and Protection, Inc. (LLP) in Tucson, AZ.

In June 1986, arrangements were made to obtain the lightning data from the SUNY-Albany network on an LLP Remote Data Processor (RDP) located at Hanscom AFB, MA. The data received were confined to the northeastern United States, Figure 1, and consisted of significant details about each strike, for example, the time of occurrence and latitude and longitude. The use of the LLP RDP in a

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5. Bent, R.B., Casper, P.W., Scheffler, T.H., and Leep, R. (1983) A unique time of arrival technique for accurately locating lightning over large areas. Preprints, Fifth Symposium on Meteorological Observations and Instrumentation (Toronto), AMS, Boston, pp. 505-511.
6. Lyons, W.A., Bent, R.B., and Highlands, W.H. (1985) Operational uses of data from several lightning positions and tracking systems (LPATS). Preprints, 10th International Aerospace and Ground Conference on Lightning and Static Electricity (Paris) AAAF, Paris, pp. 347-356.
7. MacGorman, D.R. and Rust, W.D. (1988) *An evaluation of two lightning ground strike locating systems*, Final Report, Office of the Federal Coordinator for Meteorological Services and Supporting Research, 76 pp.

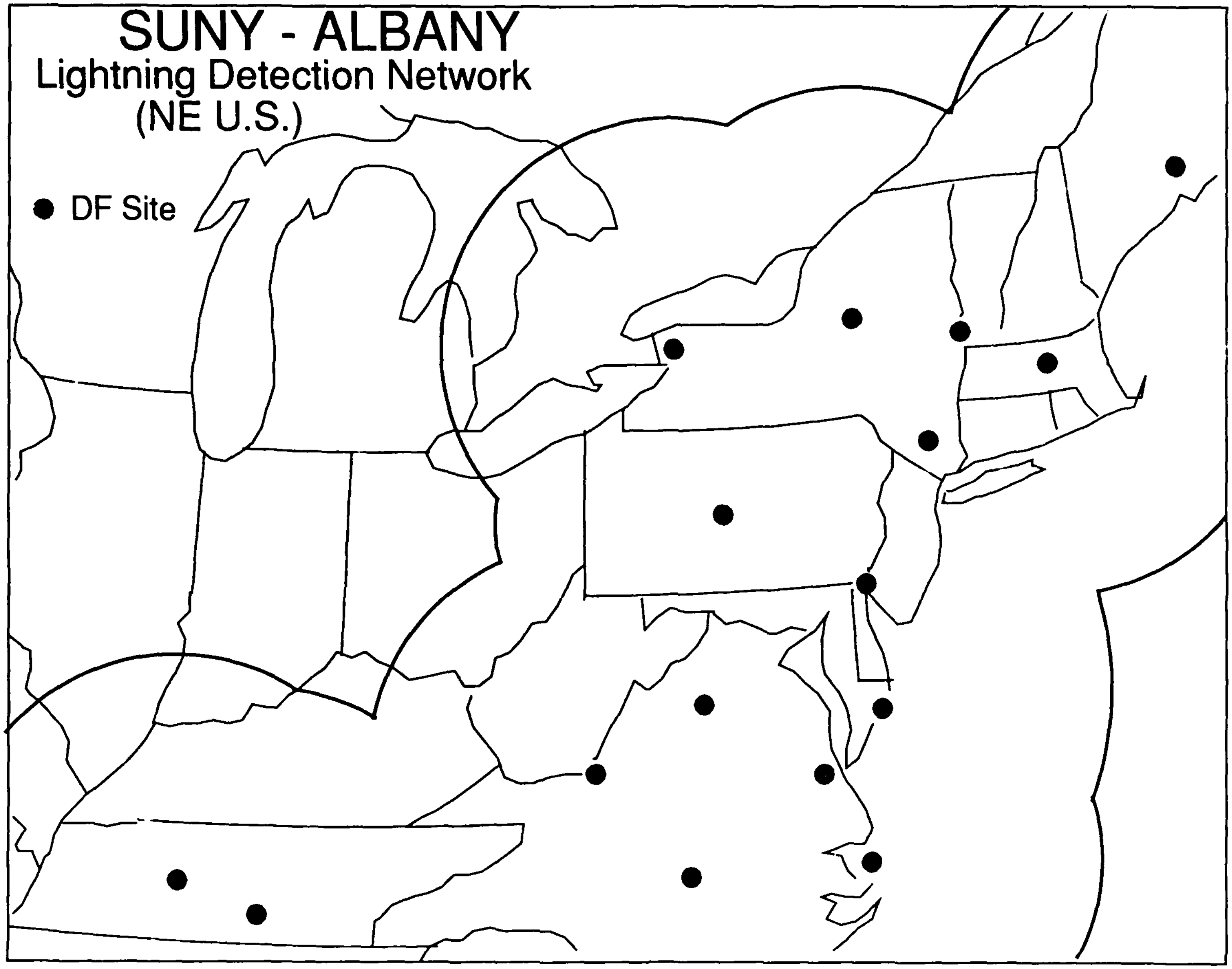

Figure 1. The State University of New York at Albany Lightning Detection Network in the Northeastern United States. Direction Finder (DF) sites are denoted by solid circles. Arcs (200-mile radius-circles about each DF) delineate the outer boundary of the network.

case-study application to real-time operation was the subject of a recent report.[8] The location of the DF's in the northeast are also shown in Figure 1 together with a boundary indicating a rough approximation of the outer limits of network coverage. It has been estimated that a DF has a detection efficiency of 80 percent cut to about 200 nmi. Strikes are detected beyond this range but with greatly decreased efficiency. It can be seen that the spacing and location of the DF's provides a zone of maximum coverage along and just west of the east coast.

2.3 Air Force Weather Observation Network

One of the principal tasks of the Air Weather Service is to man weather detachments at selected Air Force bases and provide timely weather observations for flight planning and base operations. The detachments are staffed by weather personnel whose duty is to take observations hourly and to maintain a watch so that local and special observations can be made whenever significant changes or occurrences in weather are observed.

Figure 2 shows the location of Air Force stations used in this study. A majority of the bases were located along the east coast within the higher density DF-coverage of the Lightning Network, as shown in Figure 1. Other Air Force bases were selected to extend the observation network to the outer fringe of the Lightning Network. The four stations located outside the nominal coverage area of the LDN are indicated with different markers.

Table 1 gives information about the 25 Air Force stations selected to provide a weather observation data base for comparison with the Lightning Detection Network data base. Call letters, station name, and latitude and longitude for each station are listed. The column labeled DF designates the number of network direction-finders that provide coverage to the station listed. Six stations are identified as being operative less than 24 hours per day.

3. DATA ANALYSIS

The question addressed in this study was how effective a real-time automated lightning strike location network would be in emulating a human observer. The approach used was to compare the data base of lightning strike locations generated by the SUNY-Albany Lightning Detection Network (LDN) for the months of July and August 1986 with the data base of observations (copies of the original WBAN-10s) made by observers at 25 Air Force stations during the same period.

The point should be made that this test represents a very narrow or limited application of the data collected by the Lightning Detection Network. The LDN is a regional network and it excels in an objective representation of lightning activity over a broad area.[4,8] On the other hand, the human weather observation, particularly of thunderstorms and lighting, is highly subjective. The observer's range of detection of weather phenomena varies widely as a function of restrictions to visibility, either by weather or by buildings or local topographic features. The audible detection of

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8. Brown, H.A. (1988) *Lightning Detection for an Air Force Automated Observation System*, AFGL-TR-88-0142.

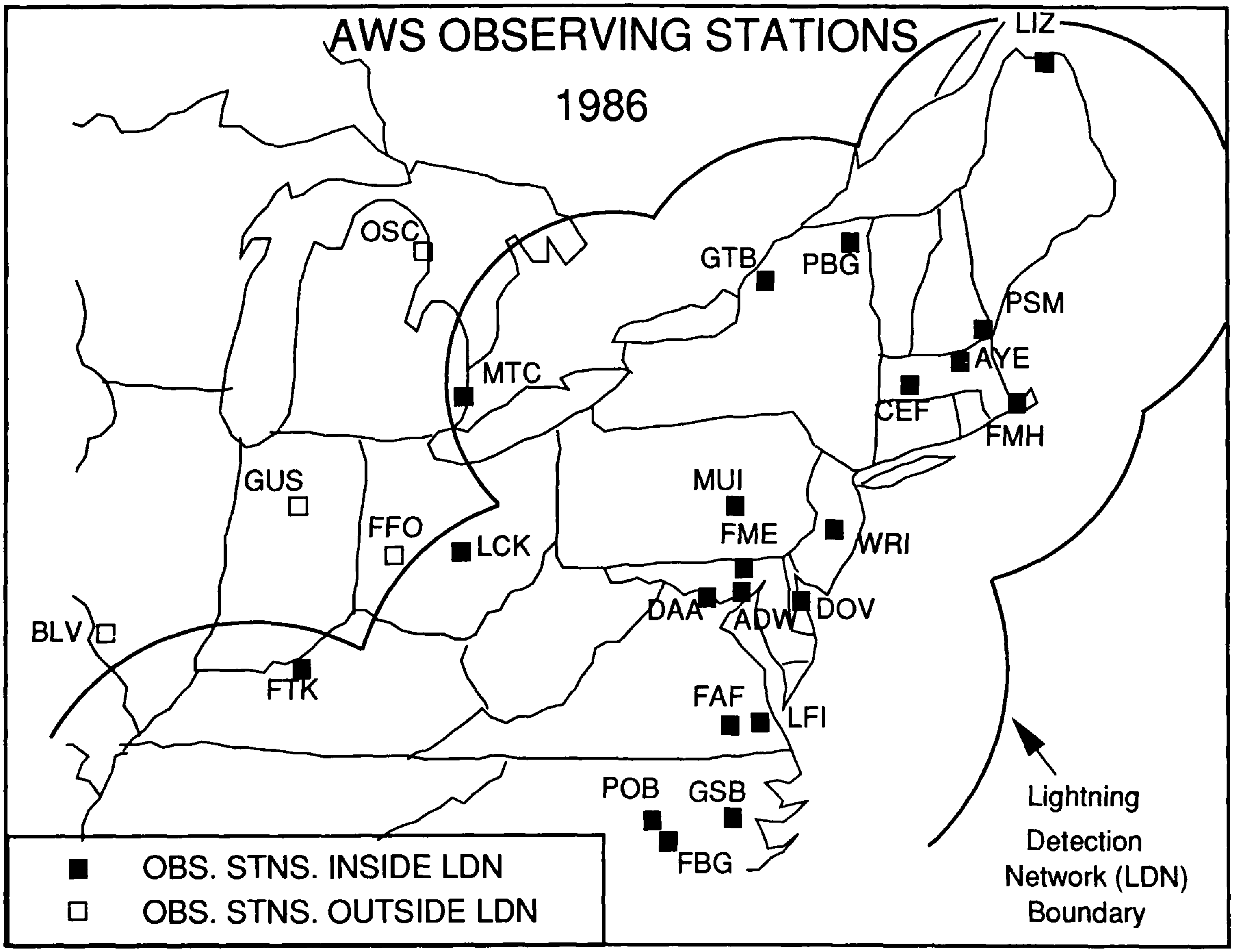

Figure 2. Weather Stations Whose Observations for July and August 1986 Were Used to Compare with SUNY (Albany) Lightning Network Observations. The outer boundary of the lightning network divides network and non-network observation stations.

Table 1. Air Force Weather Observations for the Period July-August 1986

	WEATHER STATION	LATITUDE Deg/Min	LONGITUDE Deg/Min	DF
ADW	Andrews AFB, MD	N 38 49	W 76 52	6
AYE*	Fort Devens, MA	N 42 34	W 71 36	4
BLV	Scott AFB, IL	N 38 33	W 89 51	0
CEF*	Westover AFB, MA	N 42 12	W 72 32	4
DAA	Davison AAF,VA	N 38 43	W 77 11	6
DOV	Dover AFB, DE	N 39 08	W 75 28	5
FAF*	Felker AAF, VA	N 37 08	W 76 37	7
FBG	Simmons AAF, NC	N 35 08	W 78 56	5
FFO	Wright-Patterson AFB, OH	N 39 50	W 84 03	0
FME*	Tipton AAF, MD	N 39 05	W 76 46	5
FMH	Otis ANGB, MA	N 41 39	W 70 31	2
FTK	Fort Knox AIN, KY	N 37 54	W 85 58	2
GSB	Seymour Johnson AFB, NC	N 35 20	W 77 58	6
GTB*	Fort Drum, NY	N 44 03	W 75 43	4
GUS	Grissom AFB, IN	N 40 39	W 86 09	0
LCK	Rickenbacker ANGB, OH	N 39 49	W 82 56	1
LFI	Langley AFB, VA	N 37 05	W 76 22	6
LIZ	Loring AFB, ME	N 46 57	W 67 53	1
MTC	Selfridge ANGB, MI	N 42 37	W 82 50	1
MUI*	Muir AAF, PA	N 40 26	W 76 34	6
OSC	Wurtsmith AFB, MI	N 44 27	W 83 24	0
PBG	Plattsburgh AFB, NY	N 44 39	W 73 28	4
POB	Pope AFB, NC	N 35 10	W 79 01	6
PSM	Pease AFB, NH	N 43 05	W 70 49	3
WRI	McGuire AFB, NY	N 40 10	W 74 36	5

* Less than 24-hour coverage

thunderstorms is subject to limitations due to the observer's location, the background noise level of the air base and atmospheric conditions. The visual detection of lightning, discussed in a later section, is highly dependent on day- or night-time occurrence. Other variations may also occur if the weather station is operating in a Continuous Weather Watch or a Basic Weather Watch mode.

Two basic types of weather watch have been defined in the Federal Meteorological Handbook No. 1, Surface Observations, for the Air Force. A Continuous Weather Watch (CWW) requires the observer to monitor weather conditions on a continuous basis. If there are periods when a CWW is not required to meet weather support requirements and the observer is needed to perform other essential tasks, a Basic Weather Watch (BWW) may be conducted with higher level approval. During a BWW, the observer's duties may limit his ability to view and evaluate weather conditions continuously. Therefore, observers in a BWW mode cannot be expected to detect and report all weather changes as they occur. Unfortunately, the weather logs do not indicate which mode is being followed.

For the purposes of this study, only the LDN strike data located within the "effective" range of a particular weather station will be used. This "effective" range will be discussed in more detail in the next section. In addition, the Air Force observers data base of observations will be considered as "ground truth" data and the the LDN data base of lightning strike locations will be considered the "test" data.

3.1 Lightning Detection Network Observations

The cloud-to-ground lightning strike data base was generated from the real-time data collected by the LLP Remote Data Processor from the SUNY-Albany Lightning Detection Network. Because the data base was generated from a historical playback of the data tapes, limitations were placed on the amount of detail that could be recorded. The range of weather detection by an observer, discussed in the previous section, and the uncertainty of the position accuracy of lightning strike locations led to a decision to record lightning strike occurrences within a radius of 15 nmi of each of the 25 weather stations. Figure 3 gives an example. A thunderstorm event began when the first strike occurred within this zone. If other strike failed to occur within 15 min, the event was ended and was labeled a single-strike thunderstorm. If other strikes occurred, the event was continued until the 15 min test failed. At this point of time, the event was ended and recorded as a multiple-strike thunderstorm. A single- and multiple-strike event data base was thus generated for the 25 stations.

3.2 Air Force Weather Observations

The thunderstorm data base, used in this study as "ground truth", was obtained from hard copy records of the surface weather observations (WBAN-10As) for each of the stations for the time period, July - August 1986. The data base included the time of beginning and ending of every thunderstorm event. From the Remarks column of the observation forms, each thunderstorm event was differentiated with respect to lightning type, for example, whether it exhibited cloud-to-ground (CG) lightning; cloud-to-cloud (CC) but no CG; or no lightning type. In addition, non-thunderstorm periods were differentiated when the observer reported cumulonimbus-type clouds in the Remarks column.

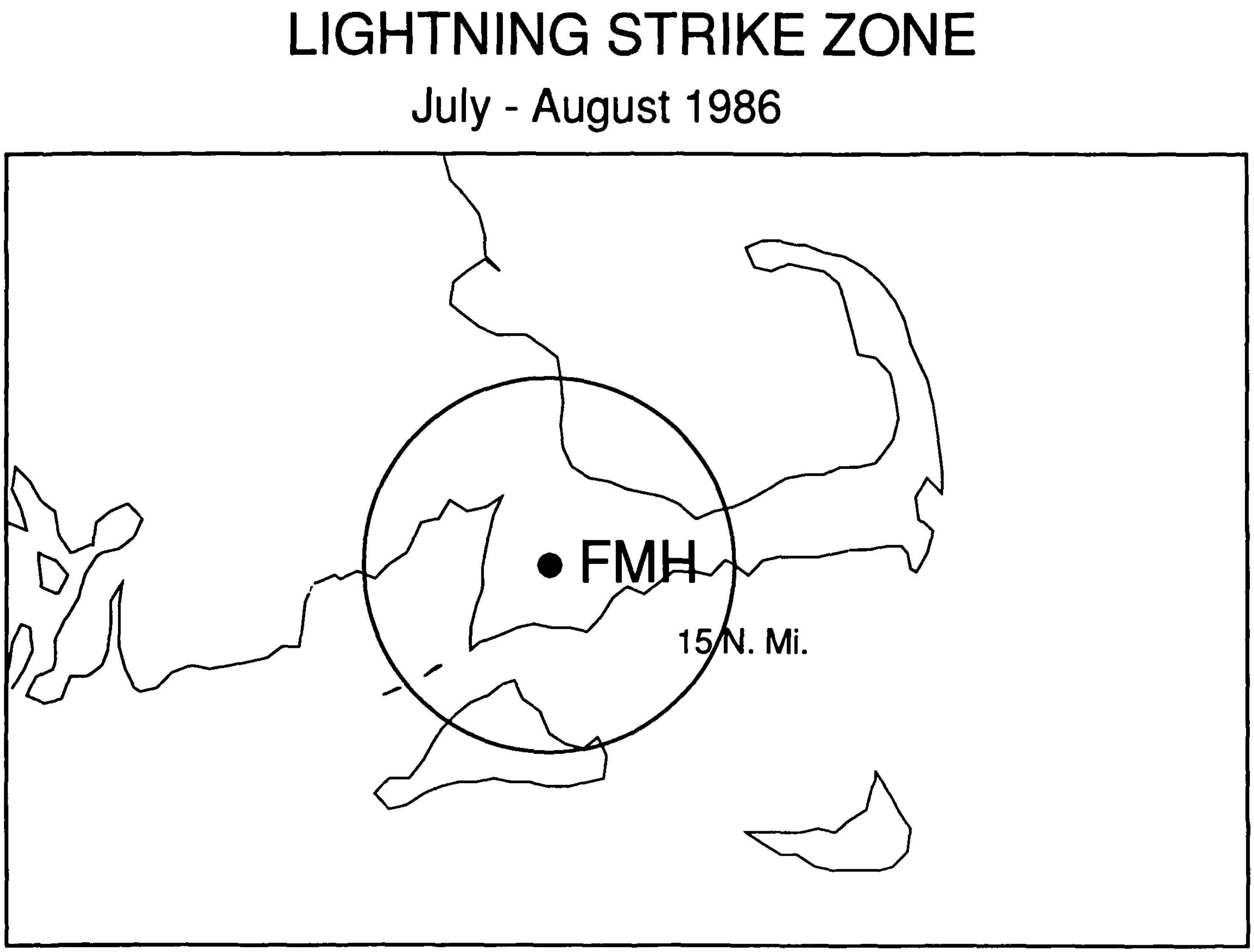

Figure 3. Illustration of the Zone (15-nmi) that was Used to Determine Lightning Strikes in the Vicinity of Each Weather Station.

3.3 Data Tabulation

A tabulation form, shown in Figure 4, was constructed in the form of a 5 × 3 contingency table for each station for each month. The classification of each network lightning strike event as a "single" or a "multiple" event provided two entries to the first column. The classification of each Air Force-observed thunderstorm by lightning type occupied three rows. The final two rows addressed the presence or absence of cumulonimbus-type clouds in non-thunderstorm events. The lightning network and the AF-observation data bases were then examined to determine the proper distribution of joint occurrences, non-occurrences or mixed-occurrences of events.

The stratification of the surface weather observations by lightning-type was originally planned to give a more complete comparison of the LDN data base with the AWS data base since the LDN detects only cloud-to-ground (CG) type lightning. Examination of the contingency tables revealed a number of cases when the LDN detected CG strikes and the observer reported CC or no lightning type. In an attempt to explain this, the diurnal variation of lightning-type observations for the AWS data base was examined in more detail.

Figure 5 shows the variation of all thunderstorm observations with time of day. The early morning minimum, the increasing activity in the afternoon and the evening maximum are clearly seen. A second curve illustrates the diurnal frequency of thunderstorm observations which had no lightning-type comments in Remarks. A third curve was derived to represent the hourly percentage frequency of thunderstorm reports that have no lightning-type observations in Remarks. An abrupt increase in the frequency of no lightning-type observations occurs just after sunrise and remains near the 50 percent level throughout the daylight hours. A decrease in this frequency occurs in the evening hours to about the 5 percent level.

This strong dependence of human lightning-type observations on time of day and the knowledge that cloud-type observations are also strongly time-dependent, gave rise to a reassessment of the evaluation of the two data bases. The decision was made to merge the 5 × 3 contingency tables into two 2 × 2 tables. One table compared the single-strike plus the multiple-strike events with thunderstorm events at each station, the other compared only the multiple-strike events with thunderstorm events. A sample diagram is shown in Figure 6.

3.4 Evaluation Parameters

Individual contingency tables were constructed for each station for the period of the study. The statistical parameters used have been described [9,10] and are illustrated in Figure 7. The ratio of the joint strike-thunderstorm events (N1) to the total thunderstorm events (N1+N3) will be designated the

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9. Donaldson, R.J., Dryer, R.M., and Kraus, M.J. (1975) An objective evaluation of techniques for predicting severe weather events, preprints, Ninth Conf. Severe Local Storms, Norman, OK, *Amer. Meteor. Soc.*, pp. 84-87.

10. Anthes, R. A.. (1983) REVIEW/Regional Models of the Atmosphere in Middle Latitudes, *Monthly Weather Review* **111**:1306-1335.

SUNY-ALBANY LDN SYSTEM

AWS OBSERVATION	LIGHTNING OB. 0-15 N.Mi.	NO LIGHTNING OB.
T, CG	Single/Multiple	
T, CC,...		
T		
NO T, Cb		
NO T OB.		

DATA TABULATION FORM

Figure 4. Tabulation Form that was Used to Compare Lightning Network Data with Weather Observations.

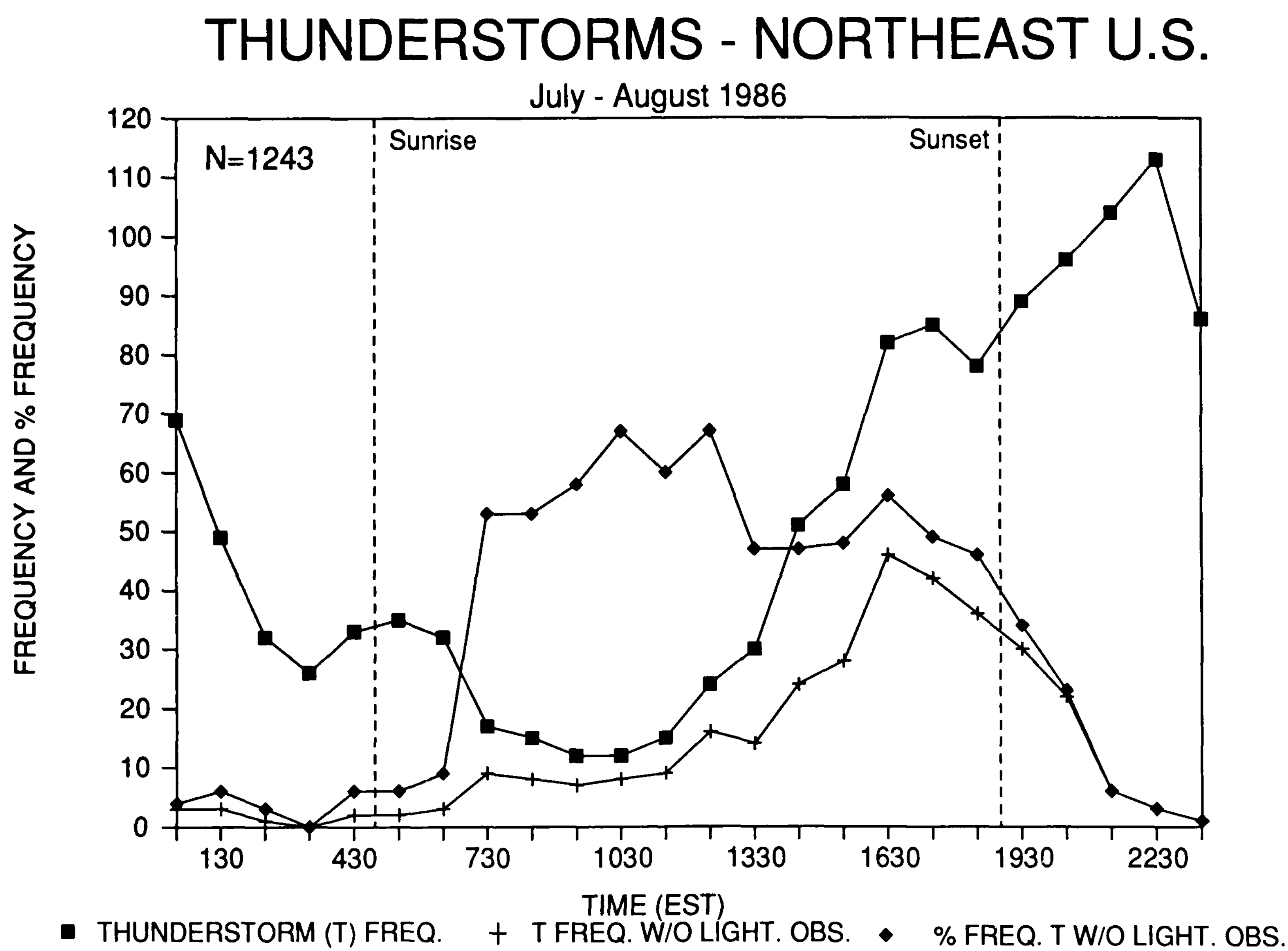

Figure 5. Diurnal Variation of Thunderstorm Observations During the Period of the Study. Two curves show the diurnal variation of thunderstorms. The first curve illustrates the frequency of all thunderstorms reported. The second curve shows the frequency of thunderstorms which had no lighting-type identified in the weather observation. The third curve shows the diurnal variation of the percentage of thunderstorms without lightning-type identification. SR and SS denote average sunrise and sunset times for the stations.

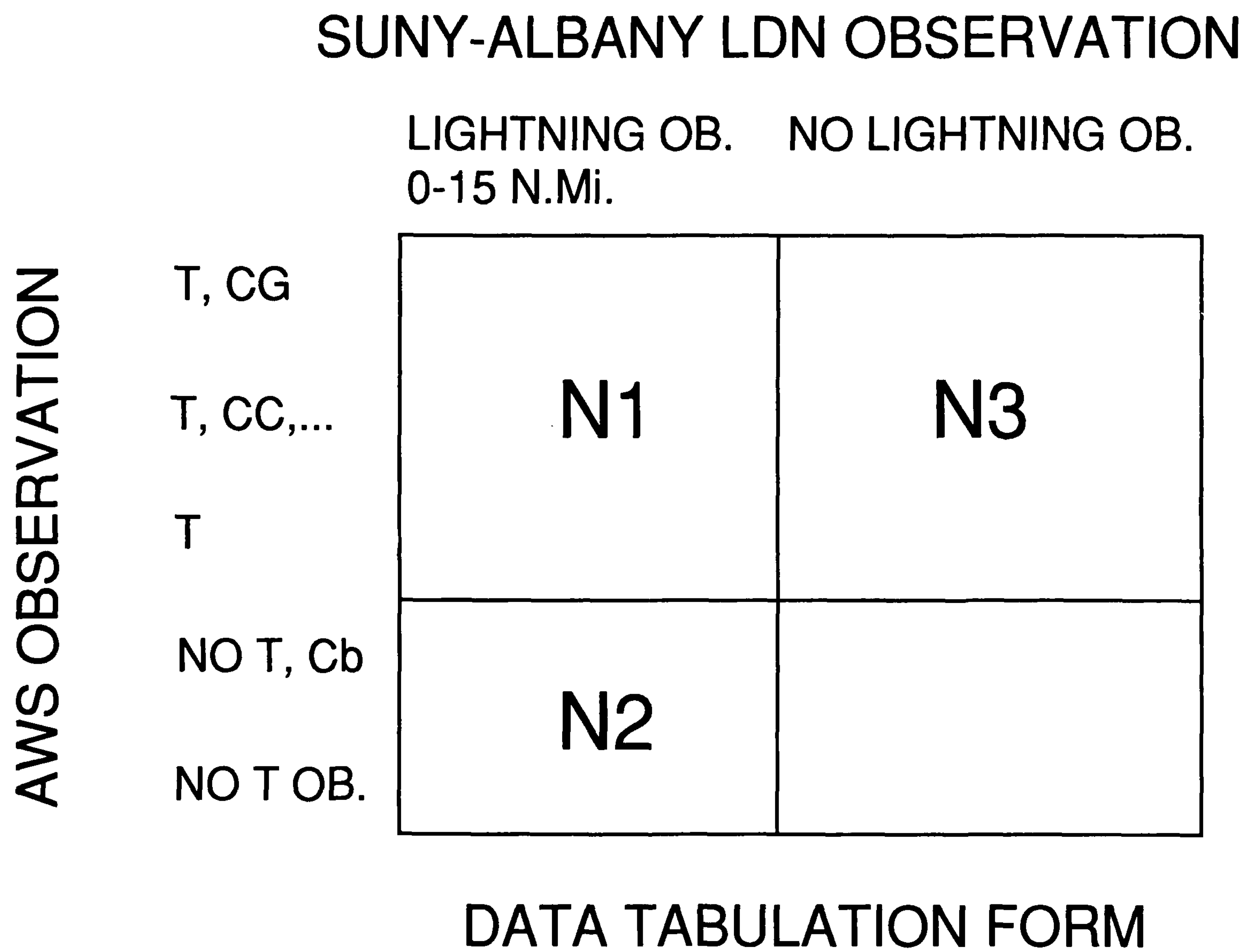

Figure 6. Illustration of the Final form Used for the Comparative Tests. N1 represents single and multiple strike events in the first test. In the second test, it represents multiple strike events only.

LIGHTNING NETWORK EVALUATION

		NETWORK OBSERVED YES	NETWORK OBSERVED NO
AWS OBSERVED	YES	N1	N3
	NO	N2	

Probability of Detection (POD) = N1/(N1 + N3)

False Alarm Rate (FAR) = N2/(N1 + N2)

Missed Threat Rate (MTR) = N3/(N1 + N3)

Critical Success Index (CSI) = N1/(N1 + N2 + N3)

Figure 7. Illustration of the Statistical Parameters Derived.

Probability-of-Detection (POD). For a POD of 1, or perfect agreement, N3 must be equal to zero. The ratio of joint strike-no thunderstorm events (N2) to the total strike events (N1+N2) will be referred to as the False-Alarm-Rate (FAR). For a FAR of 0, or no false alarms, N2 must be equal to zero. The ratio of the joint no strike-thunderstorm events (N3) to the total thunderstorm events (N1+N3) will be called the Missed Threat Rate (MTR). For a MTR of 0, or no missed threats, N3 must again be equal to zero, that is, a POD of 1 insures a MTR of 0. The fourth parameter to be determined has been referred to as the Critical Success Index (CSI). It is determined as the ratio of the joint strike-thunderstorm events (N1) to the sum of N1, N2 and N3.

4. RESULTS

In the comparison between the lightning network data and the thunderstorm observation data, we subjected the joint data base to two tests. The first test, Case 1, was the determination of the statistical parameters considering the combined single-strike and multiple-strike thunderstorm events as test data to compare with the "ground truth" human observations. The second test, Case 2, was the determination of the statistics considering only the multiple-strike events as the test data. In other words, no thunderstorm observation was generated by the lightning network unless two or more strikes occurred within the 15 nm range of a station within the appropriate time period. The results of each study are presented as a function of the DF coverage of each weather station (Table 1).

4.1 Single- and Multiple-Strike Statistics

The results of the first test are shown in Figure 8. The figure illustrates the results, as a function of the number of DFs that provided coverage for individual stations. Since the distribution of stations was not ideal over all the DF classes, stations having 0 and 1; 2 and 3; and, 6 and 7 DF coverage were combined into single classes. The parenthetical expressions at the top of the graph show the number of stations in each class. An additional class which included the statistics for all 25 stations is shown in the right-hand side of the figure.

The discussion will first concentrate on the Probability-of-Detection (POD) and the Missed Threat Rate (MTR). The POD is quite low, 0.31, for the first class of stations located at or beyond the bounds of the network, while the Missed-Threat-Rate (MTR) is quite high, 0.69. Since the MTR = 1 - POD, discussion of MTRs will be limited in the following sections. Examination of the statistics for the stations with 2 or 3 DF coverage, shows a marked increase of POD to 0.70 and a decrease in MTR. The next three classes, with greater DF coverage, show a decided improvement in POD to 0.91, 0.93, and 0.98 with corresponding decreases in MTR. The combined statistic for all 25 stations is a POD of 0.74 and a MTR of 0.26.

The False-Alarm-Rates (FAR) show an interesting distribution as a function of DF coverage. The FAR ranges from a high of 0.70 at the 0-1 DF class to a minimum of 0.33 at the 2-3 DF class, then increasing to 0.45, 0.50 and 0.52 in higher DF coverages, respectively. One explanation for this distribution is the fact that on the outer fringe of the lightning network, detection efficiency is decreased and only the most intense strikes will be detected. Since they occur at great distances from

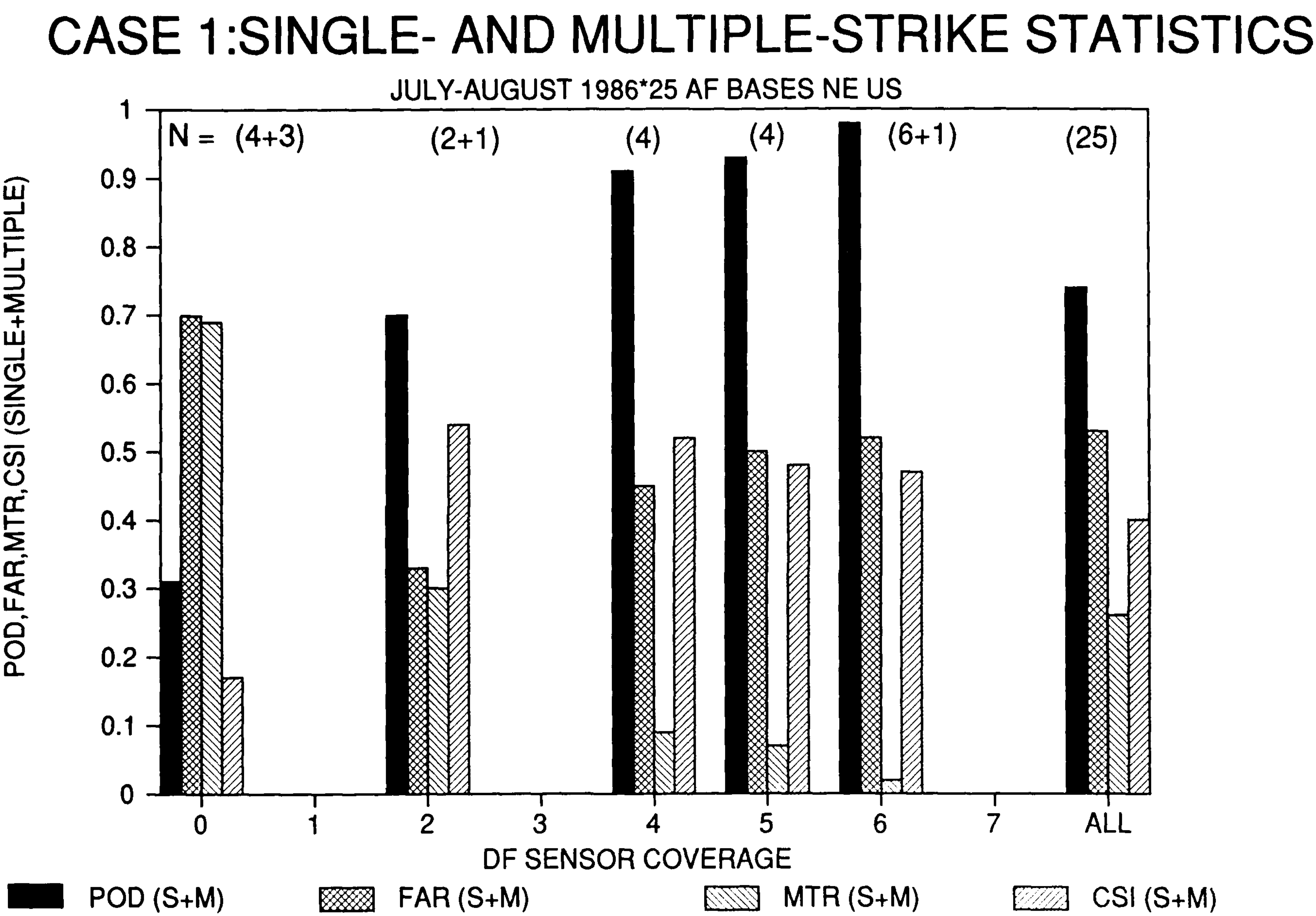

Figure 8. Statistical Results Obtained from Test 1. Network lightning events (single and multiple-strike storms) compared with thunderstorm events reported by observers. Parameter results are plotted versus DF coverage for each station. The number of stations in each class are given at the top of the figure.

the detecting DFs, they are subject to great errors in triangulation. At the other end of the distribution where stations have maximum coverage by DFs, detection efficiency is at its highest level. The distances from stations to DFs are also less and there is an increased likelihood of multiple DF detection of a strike. With the increased detection efficiency there is an increased probability of DF site errors and triangulation errors causing a false alarm at a station. The FAR in the 2-3 DF class reflects a minimum value between the two effects.

The Critical-Success-Index (CSI) incorporates both FAR and MTR components in its computation, therefore, its minimum value (0.17) at the 0-1 DF class reflects the effect of the high FAR and MTR. It is interesting to note that the maximum CSI value (0.54) is achieved by the 2-3 DF class, while the CSI values decrease in value from 0.54 to 0.52 to 0.48 in the next three classes. Even though the MTR decreases in this interval, the increase in FAR causes the CSI to decrease. Since the principal cause of this low index is the high false-alarm-rate, that becomes a prime target for further improvements.

The scores on the right-hand side of the figure are the results obtained by considering all stations in one class. The composite scores (POD of 0.74, FAR of 0.53, MTR of 0.26 and CSI of 0.40) are heavily influenced by the stations located on the outer fringe of the network. The results of this first test pose the very interesting question of the number of DFs that are required to achieve the optimal lightning strike detection for an air base.

4.2 Multiple Strike Statistics

The high false-alarm-rates in the first test suggested the need to study methods to decrease their occurrence. A second test was performed using the lightning strike data base that was restricted to two or more strikes per event. An immediate benefit, of course, was the elimination of all false alarms caused by single-strike events. The immediate penalty, however, was the creation of missed-threats by eliminating single-strike events that verified with ground-truth. The results of the second, multiple-strike, test are shown in Figure 9. The numerical values for POD are 0.15, 0.50, 0.83, 0.83, and 0.89. The values for FAR are 0.58, 0.09, 0.26, 0.33, and 0.33. The values for MTR are 0.85, 0.50, 0.17, 0.17, and 0.11. The corresponding values of CSI are 0.11, 0.45, 0.66, 0.58, and 0.62. The composite scores for all twenty-five stations are POD-0.64, FAR-0.32, MTR-.36, and CSI-.48.

The statistical changes between the first and second test can more easily be seen with a plot of the parameter differences, Figure 10. Eliminating the single-strike event as a condition for a thunderstorm occurrence at a station, has lowered the probability-of-detection in all classes (MTR increased). It is very interesting, however, that the decrease is minimal, less than 0.10, at DF coverages greater than 2 to 3. One of the most dramatic changes that occurred with the second test, however, was the substantial decrease (0.15 to 0.20) of false-alarm-rate in the higher DF classes. The other dramatic change, which is very apparent, was the increase (0.10 to 0.15) of the Critical-Success-Index in the 4- to 7-DF classes. The best class, as determined by the CSI, would be the 4-DF class which has a minimally reduced POD (minimally increased MTR), a major decrease in FAR and, as a result, a higher CSI than the other classes.

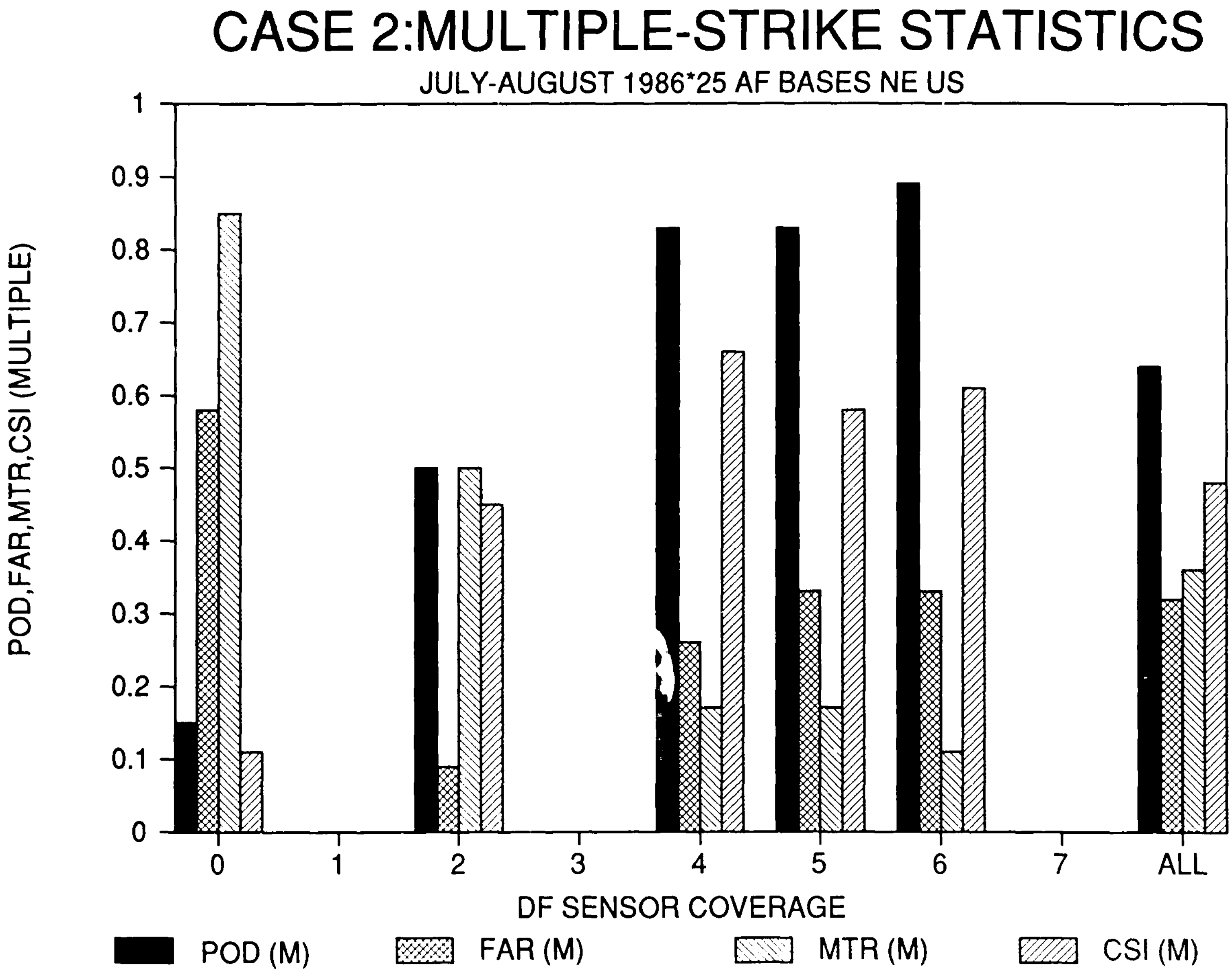

Figure 9. Statistical Results Obtained from Test 2. Only multiple-strike storms observed by the lightning network were compared with thunderstorm events reported by observers.

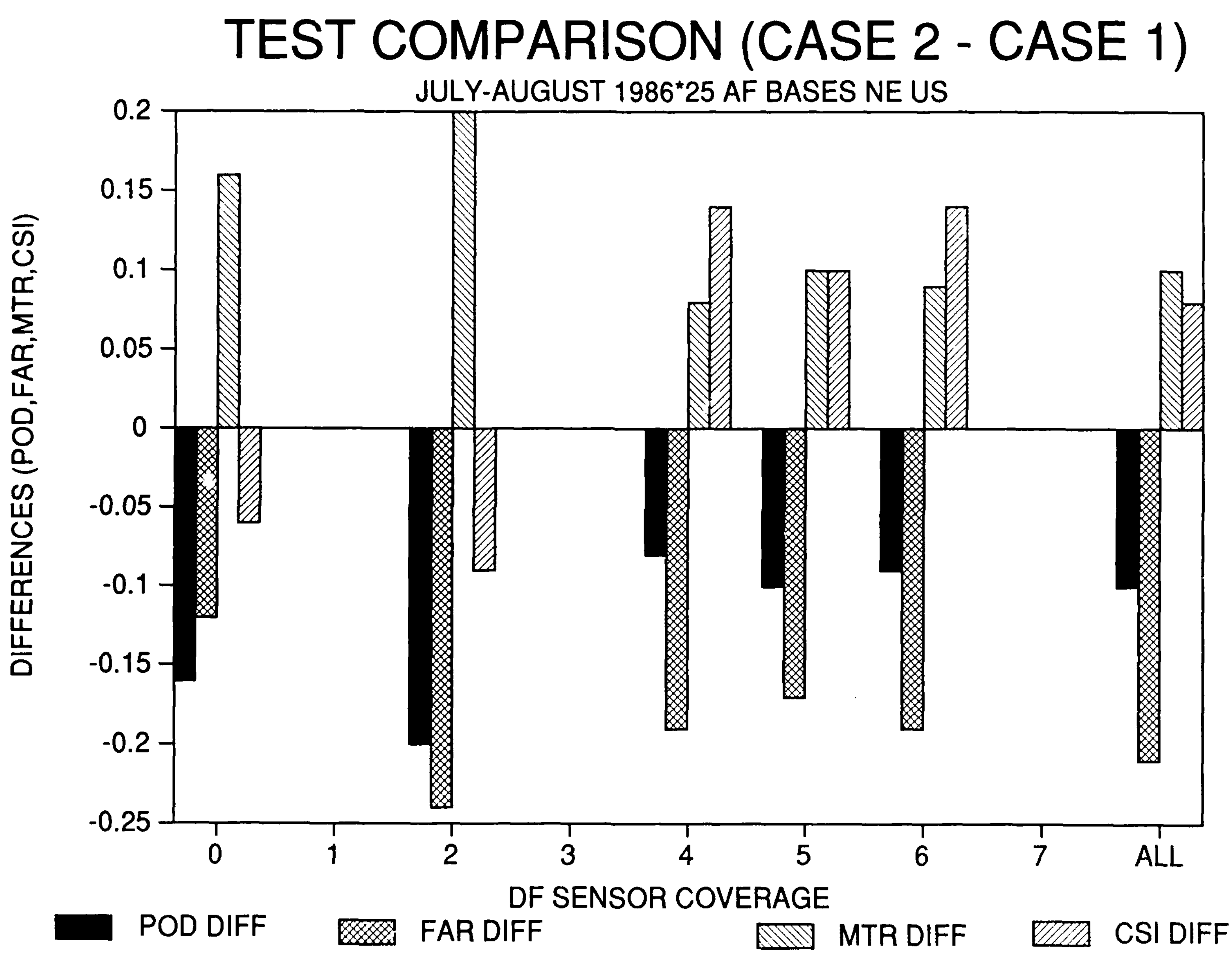

Figure 10. Changes that Occured in the Statistical Parameters Between Test 1 and Test 2.

5. SUMMARY AND CONCLUSIONS

A data base of lightning strike locations generated by an automated lightning detection network was compared with a "ground truth" data base of weather observations from 25 Air Force weather stations located in the northeastern United States during the months of July and August 1986. The purpose of the study was to determine how well the lightning detection network emulated the human observer in detecting thunderstorms that produced cloud-to-ground lightning. The radius of detection around each station was chosen to be 15 nmi. This value was chosen even though it was considered to be outside the normal audible range of the observer. The uncertainty of the accuracy of lightning strike positions and the variability of a human observer's range led to the choice of a larger radius.

Lightning strikes were tabulated in two categories. The first category was a single-strike event, that is, a strike occurred within the 15 nmi, radius of a station and in the subsequent 15 min was not followed by a second strike. The second category was termed a multiple-strike event, that is, a second strike occurred within 15 min of the previous strike. The duration of the multiple-strike event was extended until the 15 min criteria failed.

The Air Force observations were copies of the original records from the weather stations, therefore, the beginnings and endings of all thunderstorms were available together with the remarks on type and frequency of lightning, as well as the location and direction of motion of thunderstorms.

The effectiveness of the lightning network in emulating the human observer in observing thunderstorms was found to be highly dependent on the number of direction-finder sensors that provided surveillance over a particular station. Classifying stations by DF-coverage revealed that the probability-of-detection of a thunderstorm by the lightning network increased from 30 percent to 98 percent with DF coverage ranging from 0-1 DF to 6-7 DFs. At the higher DF coverage, the elimination of single strike events led to a small decrease in POD (increase in MTR).

Comparison of the lightning strike data base made up of single- and multiple-strike events with the human observations showed a consistently high false-alarm-rate. This ranged from 30 to 50 percent in the 2-7 DF coverage categories. This was a major factor in the resultant low critical-success-indexes of 45 to 55 percent in the higher DF-categories.

A second test compared the "ground truth" data base and a lightning network data base consisting only of multiple-strike events. As a result of this comparison, the probability-of-detection decreased to a much lower value at the 0-1 DF category than at the higher DF categories. Since the stations in this category were either outside or in the outer fringe of network coverage, only the strongest lightning strikes would be detected, the total strike count for a storm would be reduced, and a higher percentage of single-strike storms would be observed. The impact of eliminating single-strike events from the network data base was much less in the higher DF-categories. The probability-of-detection decreased (5 to 10 percent) and the missed-threat-rate increased in a like manner. The greatest changes observed were the large decreases in the false-alarm-rates (15 to 20 percent) at the multiple-DF stations and the sharp increases in the critical-success-indexes. Obviously, there were enough single-strike cases that did not correspond to a "ground truth" observation to indicate that in areas with multiple DF coverage a thunderstorm should not be invoked based on a single strike event.

The values of critical-success in the range of 60 to 65 percent indicate that a need still exists to improve the algorithm for thunderstorm occurrence by the lightning network. Several cases are shown in the Appendix to illustrate some typical episodes that were noted during the analysis. It is quite apparent that the choice of 15 nmi for the radius of detection was too great in some of the cases and resulted in false alarms. It is also clear that errors in triangulation caused some of the false alarms. However, a comment should also be made about the "ground truth" observations. There were cases where strikes, which were supported by satellite and radar observations, occurred less than 10 nmi from a station that was not reporting a thunderstorm. According to the rules for this study, these events were recorded as false alarms. We might, for the sake of clarity, term false alarms that are caused by a detection range that is too large or by triangulation errors, a Type I false alarm. False alarms that occur because the "ground truth" is suspect could be called a Type II false alarm. Plans call for further examination of the lightning network data and the corresponding surface weather observations. Data for July and August 1987 have been collected and lightning data obtained within 10, 20 and 30 nmi of 42 Air Force stations located along the east coast. An attempt will be made to catalog false alarms in both categories. The statistical measures of POD, MTR and CSI will also be evaluated.

An examination of stations in the 0-1 DF coverage range indicates that in this marginal region there is not much hope for significant improvement. In some cases a single strike within the 15 mile radius is the only indication of an event, so that elimination of single-strikes will decrease the POD at the site. At the same time, the accuracies of strike locations that occur at great distances from the DF network have deteriorated so that in many cases the single strike that is observed within the 15 mile radius is indeed a false alarm. This can be seen in the decreases that occurred in POD and FAR between the first and second test, Figure 10.

It should be emphasized that the lightning strike data used in this study were the output of an operational system and therefore, were not subjected to a formal edit. As such, there are a few caveats that should be stated. The first is that in any real-time operational system, communication problems occur in an unscheduled manner. Thus, the number of operational DF's that provide coverage to a particular station will vary. Individual DF sensor problems may also occur and either provide erroneous or no data for strike determination. In tabulating the data, obviously incorrect data were suppressed. On the SUNY(Albany) computer display system that was acquired in October 1986, the number of operative DF's is displayed continuously on the system monitor. Since then, a log has been maintained to tabulate DF status.

On the other hand, a few caveats also pertain to the "ground truth" data base, the human observations. They also derive from an operational network, but have been checked for errors. The thunderstorm and lightning observations, however, are qualitative determinations and vary from observer to observer. We have already discussed the variation in lightning identification from day to night. This has an impact on the verification of a cloud-to-ground lightning detection system. For example, numerous thunderstorms were reported with only cloud-to-cloud or in-cloud lightning during the entire storm. Therefore, when no lightning type is identified with a thunderstorm, the inclusion of the storm in the validation process with the lightning detection system may penalize the system.

In conclusion, the SUNY(Albany) Lightning Detection Network is capable of fulfilling a significant percentage of Air Weather Service lightning requirements. A previous study[10] illustrated the capability of the system to provide: (1) a real-time display of cloud-to-ground lightning for resource protection; (2) color coded display; (3) a resource to compute direction of movement and time-of-arrival within prescribed distances of an installation; (4) audible warning devices that activate when lightning strikes occur within a preset range, and (5) a data base for lightning climatology development.

The present effort extended the analysis to examine the ability of the system to substitute for human observers in providing observations of thunderstorms and lightning at an installation. Results, though very encouraging, indicate that further research and development is needed. In particular, efforts should be made to improve the sensor software (lightning strike definition) to avoid rejecting the few cloud-to-ground strikes that might occur in a weak thunderstorm. The probability of detecting storms would increase and the misses would correspondingly decrease. Work is also needed in improving triangulation techniques and editing algorithms. It was not possible in this study to address the position accuracy of lightning strikes, but the false-alarm-rates obtained in the results and some of the examples shown in the Appendix indicate that improvements are needed.

As an indication of the widespread interest in lightning detection systems, a multi-agency committee was formed under the auspices of the Office of the Federal Coordinator for Meteorology (OFCM) to examine the feasibility of a National Lightning Warning Network. An outgrowth of the committee's work was the establishment of a three-year demonstration of a nation-wide network. In this network, the SUNY(Albany) group combines the data from the Bureau of Land Management (BLM) Rocky Mountain Network and the National Severe Storms Laboratory (NSSL) Network with the SUNY(Albany) Network, as shown in Figure 11, and disseminates the real-time lightning locations to interested government agencies.

Based on the experience gained at AFGL since the SUNY(Albany) LDN was installed, it is quite evident that this type of network has great potential for meeting aviation requirements and represents state-of-the-art development of a real-time lightning detection capability.

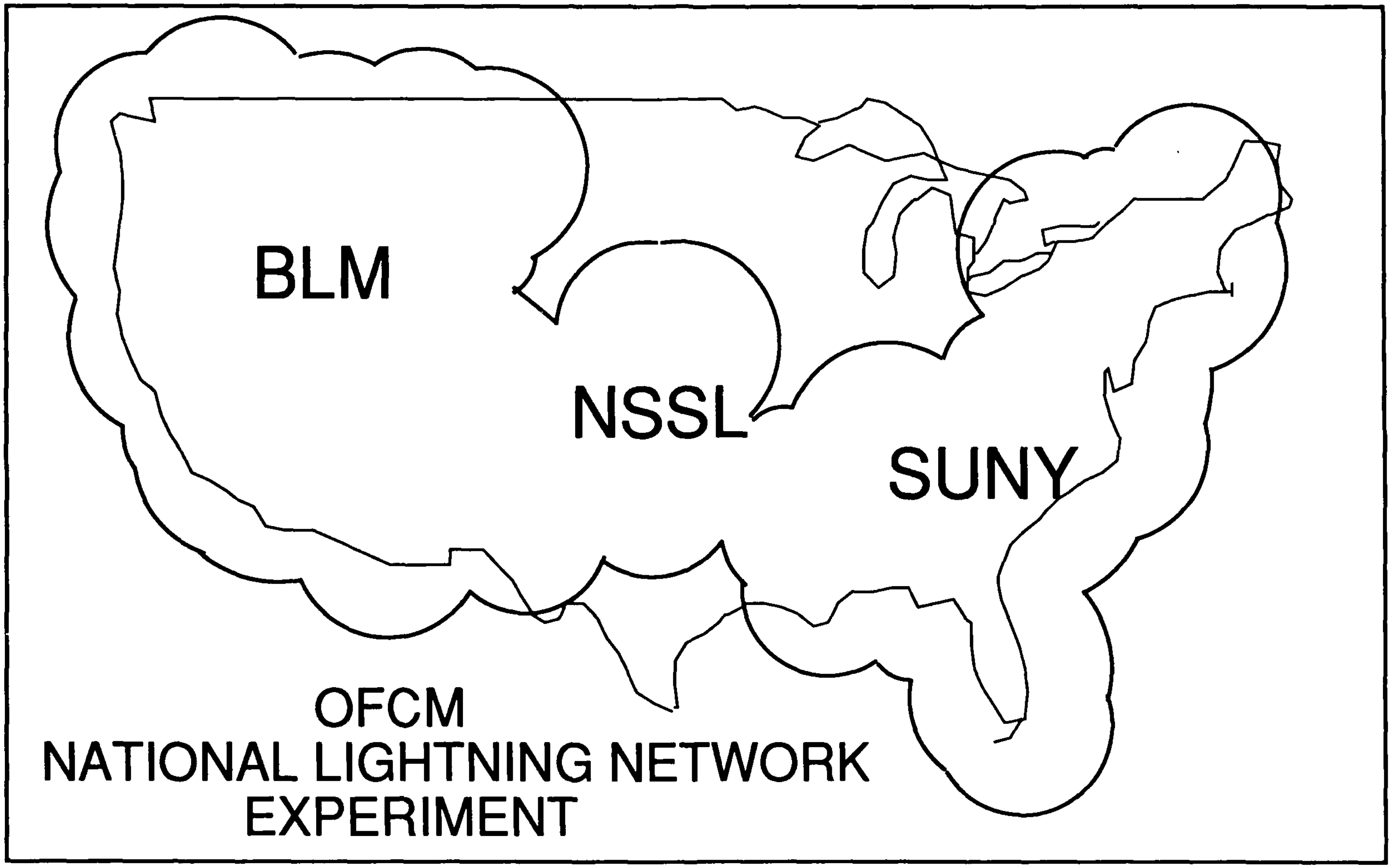

Figure 11. Demonstration National Lightning Detection Network.

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Appendix: Examples of Individual Cases

Many individual cases were examined to determine the particular details that occurred in false-alarm and missed-threat events. In the following pages some examples are shown to highlight some of the scenarios which occurred.

Visible and infra-red satellite pictures and manually-digitized-radar (MDR) maps were used, when available, to supplement the AWS observations in a "ground truth" determination for the cases. Although the first two sources do not affirm the presence or absence of lightning, they do give evidence of the existence of cells capable of producing thunderstorm activity.

CASE 1: JULY 11, 1986

A: POPE AFB, NC (POB)

This case was chosen to demonstrate a false alarm that was generated by the lightning network because the radius of detection (15 nmi) was too large, that is, a 10 nmi radius would have excluded any strikes and no LDN thunderstorm event would exist. Figure A1 is a copy of the lightning strike location chart for the period 2340 to 0040 GMT. Lightning strikes are located to the east of POB at a distance of 10 to 15 nmi and are indicated to have occurred between 2340-2359 GMT. Table A1 shows

Table A1. Weather Observations at POB

TYPE	TIME	VIS/WX	REMARKS
SA	2255	7	CB 8SE MOVG SE
SA	2355	7	30200 1378
SA	0055	7	

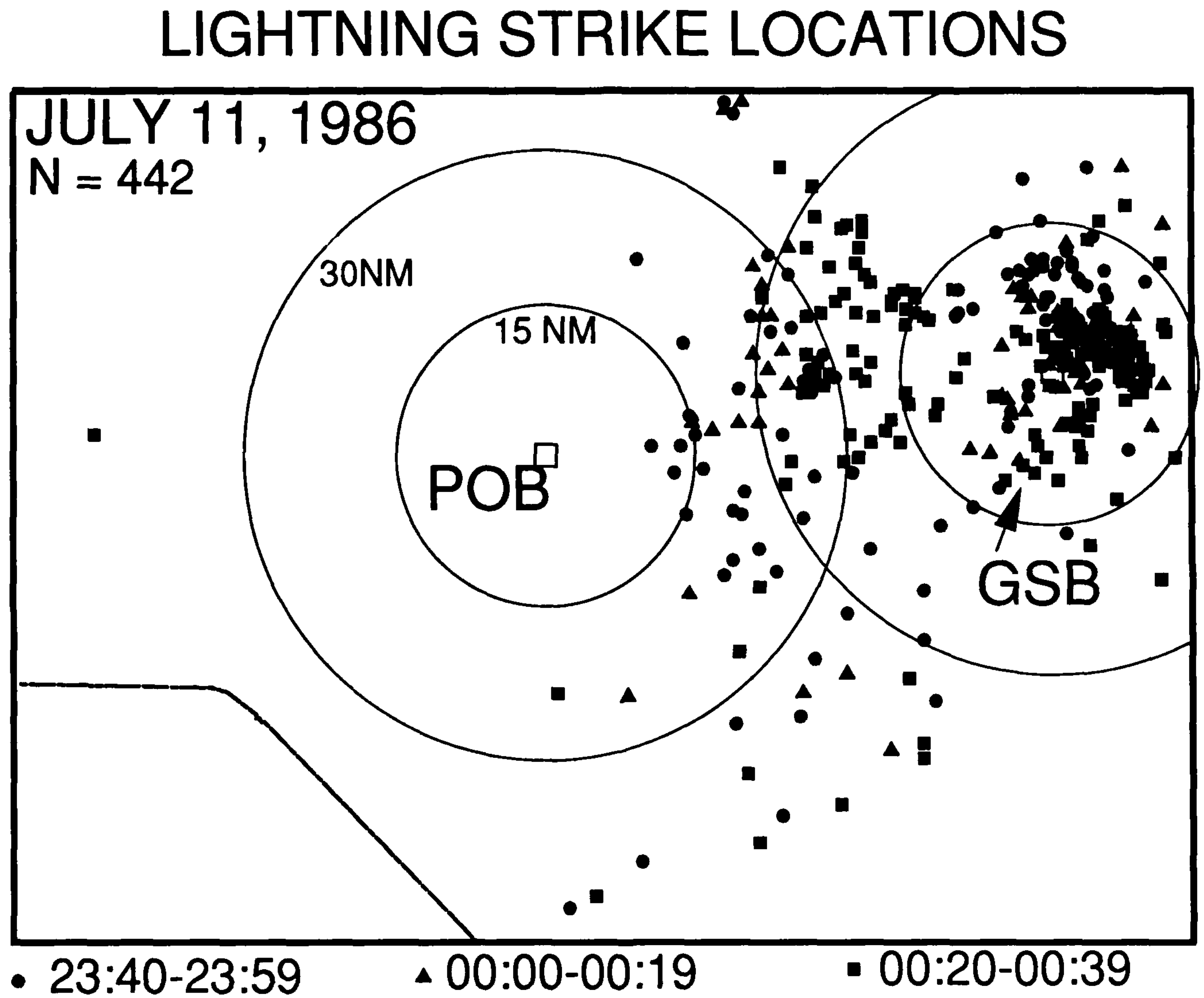

Figure A1. Lightning Strike Locations, 11 July 1986, N = 442

an excerpt from the original weather records at POB. No thunderstorms were reported during the period 2355 GMT to 0055-GMT. In an earlier observation, a cumulonimbus cloud was reported to the southeast moving away from POB. A visibility of 7 miles and the time of day are probable reasons for the lack of any distant lightning remarks.

B. SEYMOUR JOHNSON AFB, NC (GSB)

This case was selected to illustrate one of the most important features of the lightning detection network, the early warning of lightning within specified distances of air bases. Figure A1 also displays strikes in the vicinity of GSB, located about 50 nmi to the east-northeast of POB and almost hidden in the cluster of strikes. Examination of detailed maps showed that about 75 strikes occurred within 10 nmi of GSB during the period 2340-2359 GMT. The majority of these strikes occurred in the northeast quadrant and approximately 30 of them were within 7 nmi. Maps prior to and following this map indicated that the motion of the clusters of strikes was to the southeast. The observations at GSB, Table A2, indicate that the observer reported cumulonimbus-type clouds to the northwest and

Table A2. Weather Observations at GSB

TYPE	TIME	VIS/WX	REMARKS
SA	2355	7	CB 22W AND 9 NW-N MVG E
SP	0043	7 T	T W-N-NE, MOVG E OCNL LTGCGIC

north at 2355 GMT. Clusters of strikes at both locations agree with this observation. A thunderstorm, however, was first reported at 0043 GMT. In the data tabulation, this event was recorded as a verified storm detection by the lightning network with a positive lead time of 60 min. The network indicated an end to the storm about 10 min after the observer.

CASE 2: JULY 11, 1986

A: LANGLEY AFB, VA (LFI)

This case demonstrates an early detection of a thunderstorm at LFI by the lightning network. The lightning plot, Figure A2, shows strikes over a one-hour period, 2037 to 2136 UTC. The strikes are generally displaced with time from northwest to southeast. Six cloud-to-ground strikes occurred within 5 nmi of LFI during this period. Examination of the weather record at LFI, Table A3, shows a

Table A3. Weather Observations at LFI

TYPE	TIME	VIS/WX	REMARKS
SA	1955	5 H	
SA	2058	5 H	CB 13W AND 10 S MOVG SE
SP	2150	5 TRW-H	T OVHD-S MOVG SE

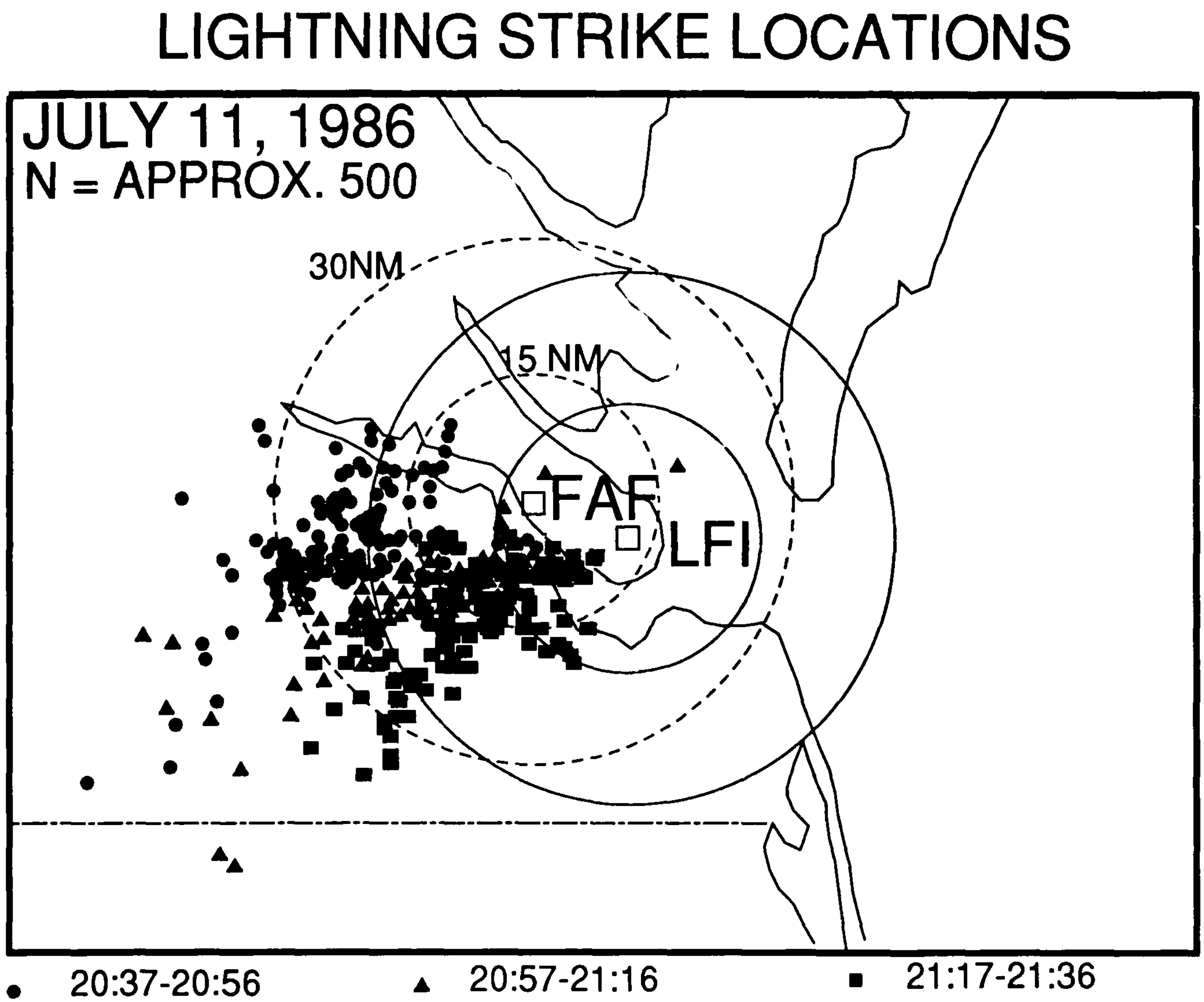

Figure A2. Lightning Strike Locations, 11 July 1986, N = Approx 500 visibility reduced to 5 miles by haze throughout the period. Cumulonimbi were noted west and south of the station at 2058 UTC and a thunderstorm with a light rainshower was reported at 2150 UTC. The restricted visibility and the time of day probably limited the observer from an earlier detection of lightning. This event was tabulated as a hit by the lightning network because the network- and observer-determined periods of activity overlapped. The network thunderstorm duration was longer due to a lead-time in detection of about one hour.

B. FELKER AAF, VA (FAF)

This case illustrates another scenario during the same weather period for a nearby station, FAF. Felker AAF is located about 12 nmi west-northwest of LFI, as shown in Figure A2. Eight lightning strikes occurred within 6 nmi of the station during the same time period and a large cluster of strikes are located 6 to 12 nmi south of the station. Examination of the weather records at FAF, Table A4,

Table A4. Weather Observations at FAF

TYPE	TIME	VIS/WX	REMARKS
SA	1956	6H	MDT CU SSW
SA	2056	6H	
SA	2155	6H	

from 1956 to 2155 UTC shows that the visibility was restricted to 6 miles by haze. Moderate cumuli were noted to the SSW at 1956 UTC but no thunderstorms or precipitation were observed throughout the period. The ground rules adopted for this study required that this event be recorded as a false alarm even though the observations at LFI and radar and satellite maps for the period supported the observations of the lightning network.

CASE 3: JULY 17, 1986

A: LANGLEY AFB, VA (LFI)

This case was selected to show a second type of false alarm. The lightning plot, Figure A3, shows strikes over a two-hour period, 0500 to 0659 UTC. Considerable lightning activity is located northeast of LFI at 30 to 50 nmi. The motion of the activity is from the northwest to the southeast. Several cloud-to-ground strikes occurred within 15 nmi (two strikes within 10 nmi) of LFI between 0520 and 0639 UTC. Examination of the weather record at LFI, Table A5, during the same time period shows no

Table A5. Weather Observations at LFI

TYPE	TIME	VIS/WX	REMARKS
SA	0455	7	
SA	0555	7	
SA	0655	7	

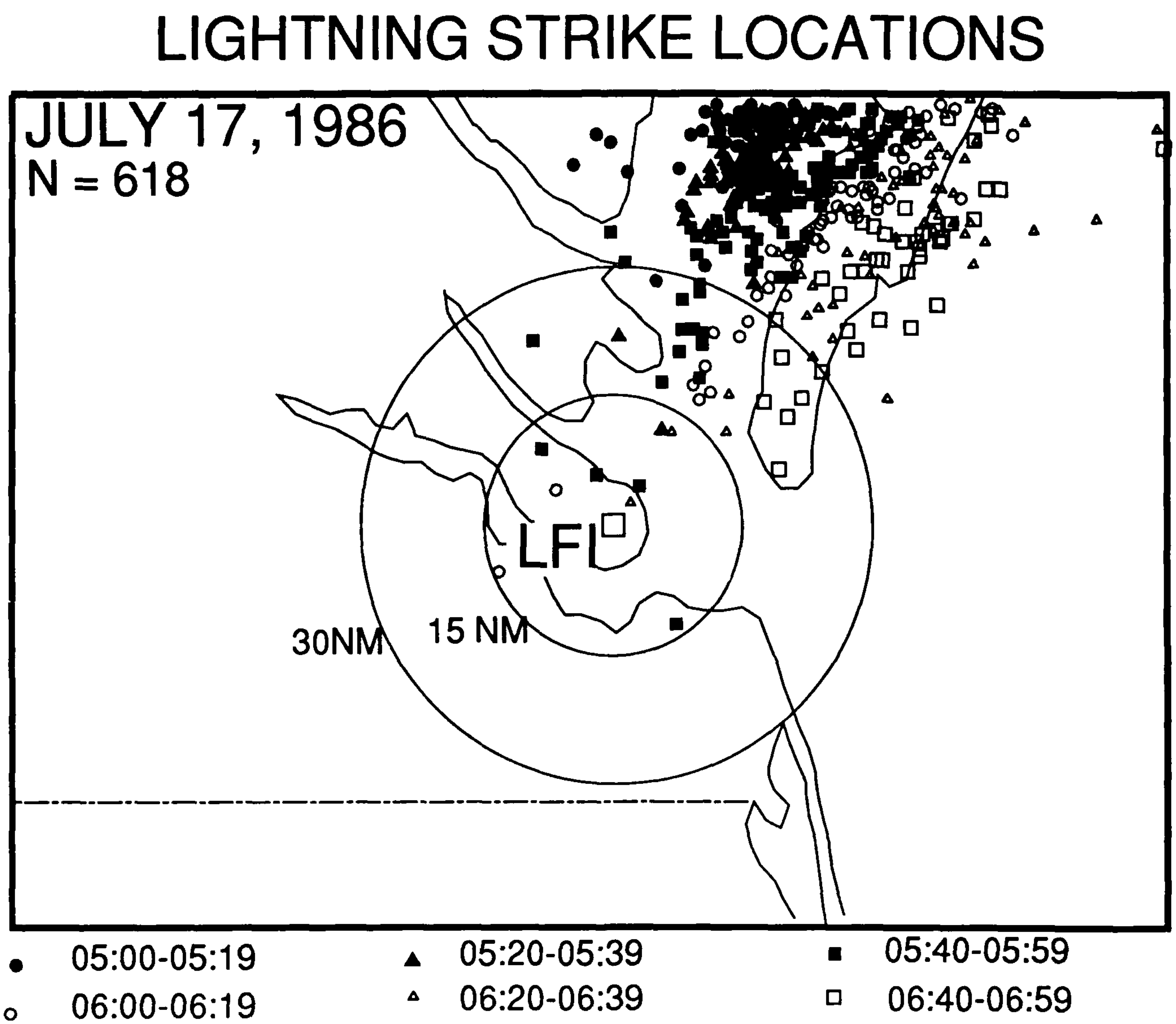

Figure A3. Lightning Strike Locations, 17 July 1986, N = 618

evidence of electrical activity. The observations at FAF also indicated no activity. The time of day was favorable for distant lightning observations but visibility at LFI was limited to 7 miles. This case was tabulated as a false alarm for single and multiple strike events. A detailed examination of the period suggests that these strikes were probably the result of mis-triangulations by the network and, in fact, occurred farther to the northeast.

CASE 4: JULY 5, 1986

A: PEASE AFB, NH (PSM)

This case illustrates another scenario encountered in the verification of the lightning strikes observations. The lightning plot chart, Figure A4, for the period 2002 to 2101 UTC show 10 CG strikes in eastern New Hampshire and off the coast of Massachusetts. One strike occurred within 15 nmi of PSM (10 nmi WSW) during the period 2022 to 2041 UTC. Examination of the weather records at PSM, Table A6, showed a thunderstorm beginning at 2026 and ending at 2119. Visibility was restricted

Table A6. Weather Observations at PSM

TYPE	TIME	VIS/WX	REMARKS
SA	1956	3 RW-F	F DEP 50
SP	2026	3 TRW-	T WNW MOVG ESE OCNL LTGCGCA
SP	2038	1 TRW-	T OVHD MOVG ESE
RS	2058	1 1/2 TRW-F	T OVHD-S MOVG ESE OCNL LTGICCA
SP	2119	1 RW-F	T MOVD E CB SW MOVG E

(3 to 1 mile) during the period of the thunderstorm by rain and fog. Cloud-to-ground lightning was reported by the observer only on the 2026 UTC observation. This episode was tabulated as a single-strike event for the lightning network and recorded as a confirmed hit as it coincided with the period when cloud-to-ground lightning was observed. However, if we followed the rationale that a single-strike event could not trigger an event at a station, this episode would be tabulated as a missed threat.

CASE 5: JULY 27, 1986

A: OTIS ANGB MA (FMH)

During this episode, the observer at FMH reported thunderstorms over a 1 1/2 hour period, (Table A7). Cloud to ground lightning was reported on the 0955 observation. During the same time period, 0900 to 0959, the network, observed only a few strikes in the 15 to 30 nmi range, as shown in Figure A5. No strikes were observed within 15 nmi of FMH. One explanation may be that the observer saw CG strikes that exhibited sufficient cc characteristics to cause the LLP sensor software to reject them. Another possibility was that the intensity of the strikes was insufficient to be sensed by the nearest DFs. It should be noted that FMH, Table 1, is under 2 DF coverage. This event was tabulated as a missed threat in the comparative analyses.

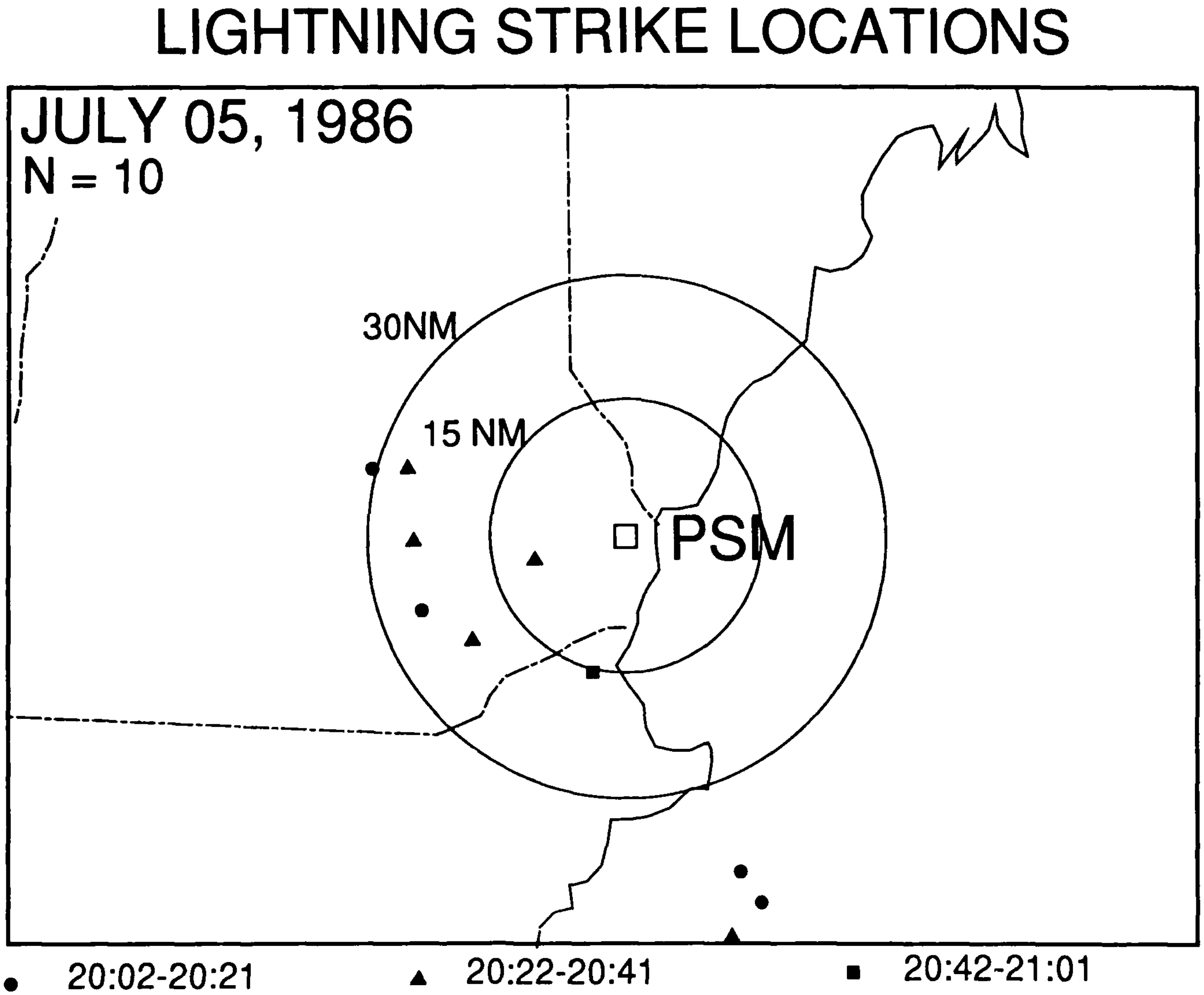

Figure A4. Lightning Strike Locations, 5 July 1986, N = 10

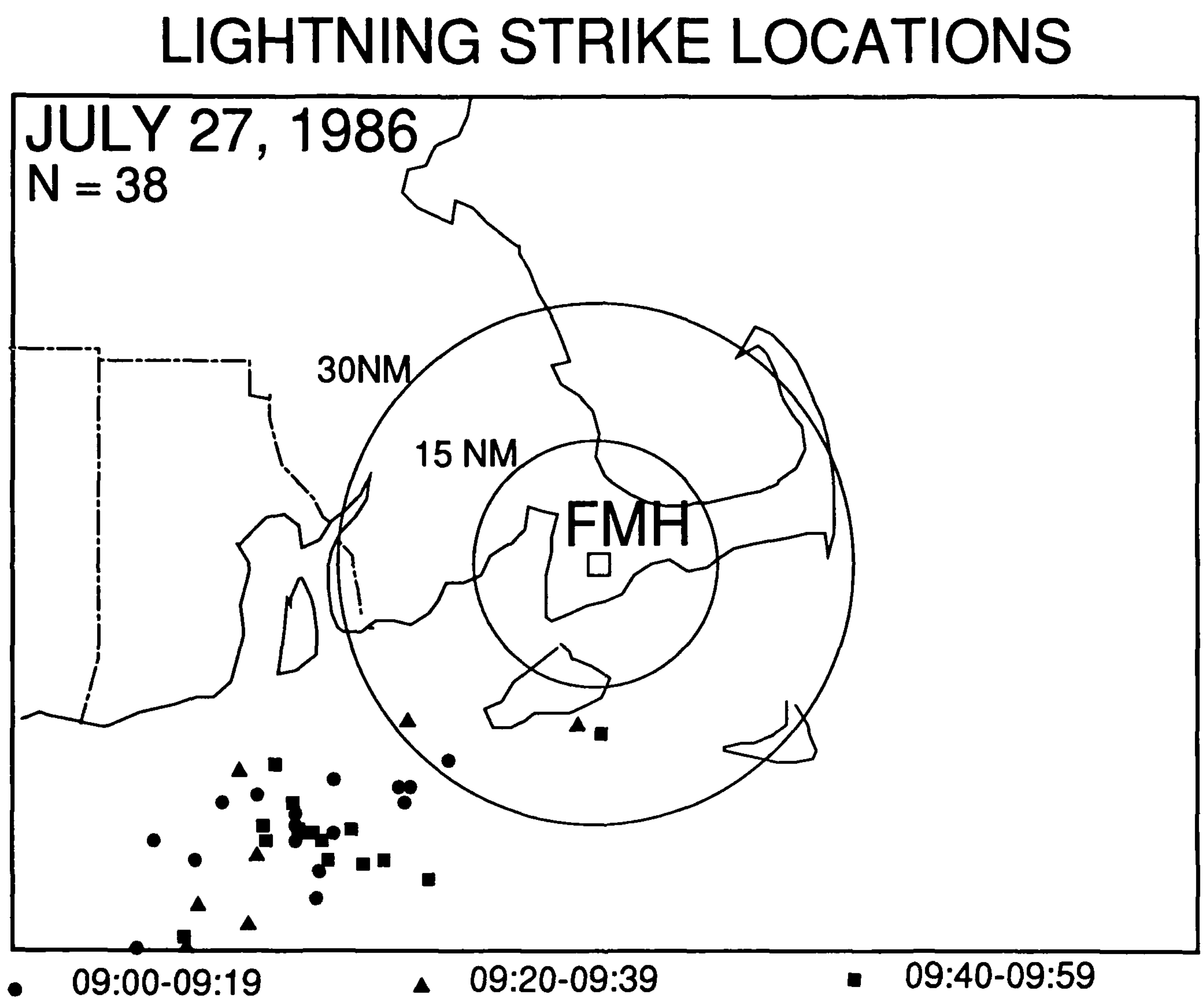

Figure A5. Lightning Strike Locations, 27 July 1986, N = 38

Table A7. Weather Observations at FMH

TYPE	TIME	VIS/WX	REMARKS
RS	0855	8 T	T N MOVG NE-E OCNL LTGCCIC
SP	0907	7 TRW-	T N MOVG NE-E OCNL LTGCCIC
SP	0918	2 TRWF-	T OVHD MOVG E OCNL LTGCCICCA
SP	0935	3/4 TRF	T OVHD MOVG SE OCNL LTGCCICCA
RS	0955	1 1/2 TR-F	T OVHD MOVG SE OCNL LTGCCICCCCA
SP	1031	1 1/2 R-F	T MOVD SE

CASE 6: AUGUST 27, 1986

A: ANDREWS AFB, MD (ADW)

This case was selected to illustrate some of the events that occurred in areas that were under multiple DF surveillance. This thunderstorm, as indicated in Table A8, was the third occurrence

Table A8. Weather Observations at ADW

TYPE	TIME	VIS/WX	REMARKS
SP	2208	6 TRW-	T S MOVG E OCNL LTGICCG
SA	2255	7 TRW-	T S MOVG E OCNL LTGICCG
SP	2314	7 RW-	T MOVD E

within four hours at ADW and the observations indicate that it was not an intense storm. The lightning strike chart, Figure A6, for the corresponding time shows considerable activity to the southeast of ADW. Only one strike, however, was observed within 15 nmi of the station. As in the previous case, two reasons can be presented to explain the lack of corresponding lightning strike observations by the network. The first is that the DF software rejected the CG strikes because they were misinterpreted as CC strikes. The second explanation is that the strikes lacked the intensity to register with any DF in the area. In this particular study, however, ADW was within the detection range of 6 DFs. In the tabulation of hits and misses, this episode was recorded as a single-strike hit by the network for the first test and a missed threat by the network for the second test which treated multiple-strike events only.

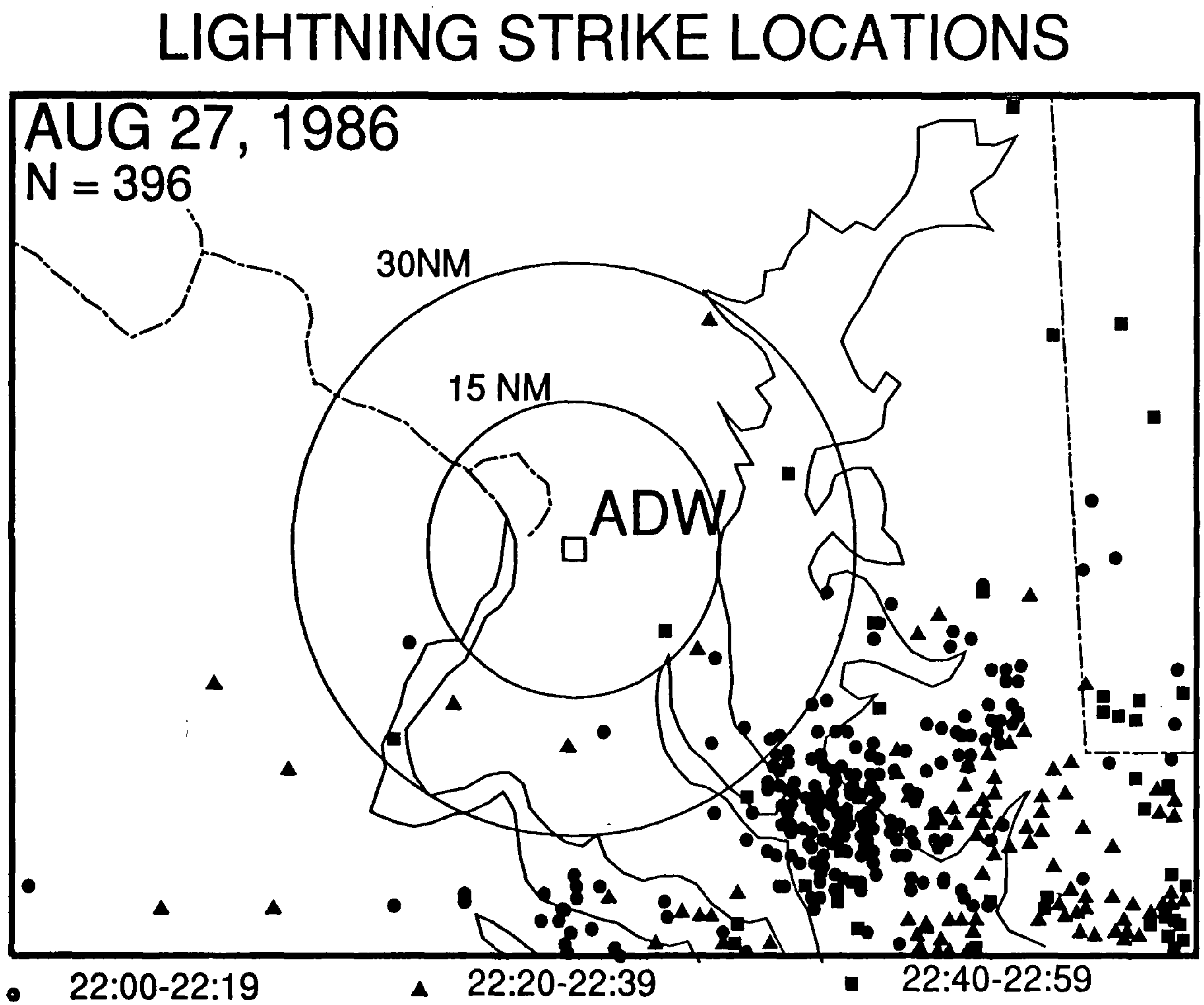

Figure A6. Lightning Strike Locations, 27 August 1986, N = 396